STELLAR POPULATIONS AND THE STRUCTURAL PROPERTIES OF SIX ULTRA-FAINT DWARF GALAXIES

B.K.S. Perera[1*], J.V. Wijesekera[2], P.L.V.J. Sigera[3], K.S. Rathnayake[1], H.R.S. Udani[1], W.C.S. Senarath[1], H.M.K.G.A. Herath[1], K.A.C. Nilmini[1], A.M.C.I. Abeyratne[1], P.V.N.D. Wimalaweera[1], B.V.A. Chathuranga[4]

[1]Institute of Astronomy, Sri Lanka
[2]University of Padova, Italy
[3]University of Ruhuna, Sri Lanka
[4]The Open University of Sri Lanka

INTRODUCTION

The Dwarf Spheroidal Galaxies (dSph), which are satellite galaxies orbiting the Milky Way, provide a rare opportunity to research galaxy formation and evolution by observing the photometric properties of the resolved stellar populations. These galaxies are known as ultra-faint dwarf (UFD) galaxies due to their extremely low surface brightness, which are approximately 100 orders fainter than that of the classical dwarf galaxies. The UFD are the oldest, most metal-poor, darkest matter-dominated (DM) and least chemically advanced stellar systems known(Wyse & Gilmore, 2007).

Globular clusters (GCs) are among the oldest structures in the universe. Current models favour GC formation via the collapse of cold gas within a larger galactic environment(Gnedin & Prieto, 2009). Due to the simplicity and extreme ages, GCs and dwarf galaxies can be useful windows into the early stages of galaxy formation. Several studies have found the existence of additional dwarf satellites around the Milky Way galaxy(Willman et al., 2005). UFD galaxies are fainter than a typical GC. Spectroscopic observations of the UFD galaxies have shown that they are excellent candidates for demonstrating the existence of fossil galaxies. Colour magnitude diagrams (CMDs) show that the UFDs are dominated by stellar populations that are older than 10 Gyr (Okamoto, Arimoto, Yamada & Onodera, 2012), and spectroscopy of their giant stars shows low metallicity measurements(Journal, 2008).

The Star formation history (SFH) of a galaxy/cluster can be characterised by isochrones. An isochrone specifies the location in the CMDs of stars with the same age and metallicity(Conroy, 2013). The turnoff point of the main sequence can be used to estimate a cluster's age. In this paper, we present the SFHs of six UFD galaxies: Bootes I (Boo I), Canes Venatici II (CVn II), Coma Berenices (Com Ber), Hercules, Leo IV and Ursa Major I (UMa I), all located in the galactic halo. For our analysis, high-precision photometry obtained from the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST) is used. We estimate the age, metallicity $[Fe/H]$ and abundance of α elements $[\alpha/Fe]$ using the Dartmouth Stellar Evolution Program (DSEP)(Dotter et al., 2008). Products of nuclear He-burning such as C, O, Ne, Mg, Si, S, Ar and Ca are the α elements. The higher the α content, the redder will be the CMD. In this research, we did not use any method to remove field stars. So, there is a photometric uncertainty.

METHODOLOGY

The calibrated data used in this paper to plot the CMDs of six UFD galaxies were obtained from deep optical images of each galaxy (Table 01)[1] using the F606W (broad V) and F814W (I) filters on the Advanced Camera for Surveys (ACS) (GO-12549; PI Brown). These six galaxies were chosen to provide a representative sample of UFDs with integrated luminosities far below those of the classical dSphs(Brown et al., 2014).

The CMD (I vs V-I) for each UFD were plotted and the following key properties were observed; Main Sequence (MS), Main Sequence Turn Off (MSTO), Horizontal Branch (HB), Sub Giant

[1] The data were extracted from, doi:10.17909/T99H5G in FITS format

Branch (SGB), Red Giant Branch (RGB) and possession of Blue Straggler stars (BSS). Customarily, the MSTO is used to date the stellar populations. We derive the values of age, distance and reddening that provide the best fit between the isochrones and the observed CMD by using equations (1) - (5). The relevant python code was used to derive the CMDs of six UFDs[2] and NGC2808[3].

$$V_{best\ fit} = V_{isochrone} + (m - M)_0 + A_V \quad [1]$$

$$I_{best\ fit} = I_{isochrone} + (m - M)_0 + A_I \quad [2]$$

$$(m - M)_0 = 5 - 5\log(d) \quad [3]$$

$$A_V = 3.1E\ (B - V) \quad [4]$$

$$A_I = 1.8E\ (B - V) \quad [5]$$

Table 1: The observational data for the six UFD galaxies are shown in the following table[4]. The table shows the astronomical position of the UFDs and the Hubble exposure times in each filter band.

Name	R.A. (J2000)	Dec.(J2000)	Exposure per tile (s)		Tiles
			F606W	F814W	
Bootes I	14:00:04	+14:30:47	2340	2200	5
Canes Venatici II	12:57:10	+34:19:23	20850	20850	1
Coma Berenices	12:27:21	+23:53:13	2340	2200	12
Hercules	16:31:05	+12:47:07	12880	12745	2
Leo IV	11:32:57	-00:31:00	20530	20530	1
Ursa Major I	10:35:04	+51:56:51	4215	3725	9

The main focus areas in this research were age, metallicity and abundance of α elements and possession of BSS. To better approximate the age, $[Fe/H]$ and $[\alpha/Fe]$ of stellar isochrones, we generate them using the DSEP. We assume as $[\alpha/Fe] = 0.4$ an appropriate value for old metal-poor populations, such as those in the Galactic halo. The best fit was found for each CMD by these Isochrones. The SGBs and the RGBs are more sensitive to α content variation than the MSs, which almost overlap with each other. This is the relation of α elements to isochrone. The CMD and the isochrone of each UFD were compared with the CMD distribution of NGC 2808 (Nardiello et al., 2018). It is an old galactic GC that incidentally hosts multiple stellar populations (Jain, Vig, & Ghosh, 2019).

Since the members of UFDs or GC have similar properties (age and metallicity), isochrones can be used to date them. Isochrones can be simulated at any age by taking any stars in the initial population, evolving it forwards to the desired age using computational simulations, and plotting the star's luminosity vs. temperature on the Hertzsprung-Russell (HR) diagram. The resulting isochrone can be compared to the observational CMD to compare how closely they fit. If they fit well, the isochrone's assumed age is the same as the actual age of UFDs' or GCs'. A detailed explanation of the DSEP can be found in Dotter et al., (2007) and a comparison with other models (Padova, VR, Y^2, BaSTI) can be found in Dotter et al. (2008).

RESULTS AND DISCUSSION

[2] https://github.com/veelochanasigera/UFDG_isochrone_fitting

[3] https://github.com/veelochanasigera/NGC2808_isochrone_fitting

[4] extracted from https://archive.stsci.edu/

The stellar populations of the six UFDs were studied using HST photometry. Figure 2 presents the CMD of each UFD, which tend to be very similar, meaning that the population ages and metallicities are also very similar. $[Fe/H]$ of the UFD galaxies are; -2.40 in Coma Berenices, -2.45 in Bootes I, -2.49 in Ursa major I, -2.49 in Hercules, -2.49 in Canes Venatici II, -2.30 in Leo IV. We plotted these CMDs according to two values of Y; $Y = 0.33$ and $Y = 0.245 + 1.54\,Z$. $Y = 0.33$ indicates that it has a 33% abundance of Helium.

These dim satellites contrast with the brighter dSphs, which all have stars that are older than 10 Gyr. The similar feature shared by these galaxies' CMDs suggests that they have similar stellar populations and SFH(Brown et al., 2014). Ages of the UFDs are 14.80 Gyr in Coma Berenices, 13.80 Gyr in Bootes I, 14.80 Gyr in Ursa major I, 14.80 Gyr in Hercules, 14.80 Gyr in Canes Venatici II and 14.10 Gyr in Leo IV. A star's turnoff point (MSTO) is the point on the HR diagram where the star evolves from its hydrogen burning phase into its next stage. In all the six CMDs of UFD galaxies, MSTO is less than -0.50 magnitude, which implies the older stellar populations.

In each CMD, there might be a few BSS that are popular in old stellar populations that fall to the blue and shine brighter than the dominant MSTO. BSSs are stars found along an extrapolation of the MS in a region brighter and bluer (hotter) than the optical CMD's turnoff (TO) stage(Ferraro, Lanzoni, Dalessandro, Mucciarelli, & Lovisi, 2015).

Since the stars in a cluster are formed at roughly the same time, all stars in a HR diagram for a cluster should lie along a precisely described curve set by the cluster's age with individual stars' positions on that curve determined solely by their initial mass. BSS seem to be exceptions to this law with masses of two to three times those of the majority of the MS cluster stars. In spiral galaxies, GCs are mainly located in the galactic halo. They are typically older, larger, denser and have fewer heavy elements than open clusters, located in spiral galaxies' disks. NGC 2808 is a GC in the constellation Carina within the halo of the Milky Way galaxy. It is one of the most luminous GCs in the Galaxy. Also, it is one of the most magnificent, especially in terms of its CMD(D'Antona et al., 2005).

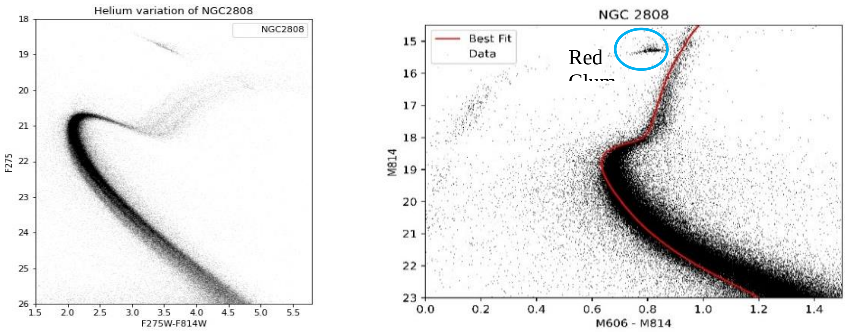

Figure 1:The colour-magnitude diagrams (F275W vs F275W-F814W and F606W vs F606W-F814W) of the globular cluster NGC2808 are shown in this figure. In the left plot the divided isochrone lines indicate the helium abundance in NGC2808. The isochrone for the plot F606W vs F606W-F814W was generated using the Dartmouth Stellar Evolution Database[5], and the photometric data of the stars were extracted from the Mikulski Archive for Space Telescopes Website[6].

The CMD (F606W vs F606W-F814W) of NGC 2808 has a sharp MSTO when compared with the six UFD. This means that this GC is much younger than UFD galaxies. Its age is around 10.20 Gyr based on the calculations we did using DSEP. The graph on the left, in Figure 1 depicts the CMD (F275W vs F275W-F814W) of same the GC. This figure (F275W vs F275W-

5 (http://stellar.dartmouth.edu/models/)
6 https://archive.stsci.edu/prepds/hugs/

F814W) illustrates the Helium variation of the NGC 2808. The Dartmouth isochrone generator was used to determine the age of the GC and the properties of the CMD of NGC 2808 were used as a reference. In this research, we analysed only the He variation for NGC 2808. The maximum Helium variation correlates with the cluster mass and with the HB extension because Helium is the second parameter of the HB morphology (more analytical details of this dependence will be proposed in the next project). Also, GCs possess more metallicities than UFDs. This can be demonstrated by the red clump seen in the first figure of the GC which is not visible in any of UFDs (Figure 2). A red clump is a clustering of red giants in the HR diagram. Generally, red clumps have more metallicities. NGC 2808 has a metallicity value of -1.24 which is comparatively higher than all the six UFDs.

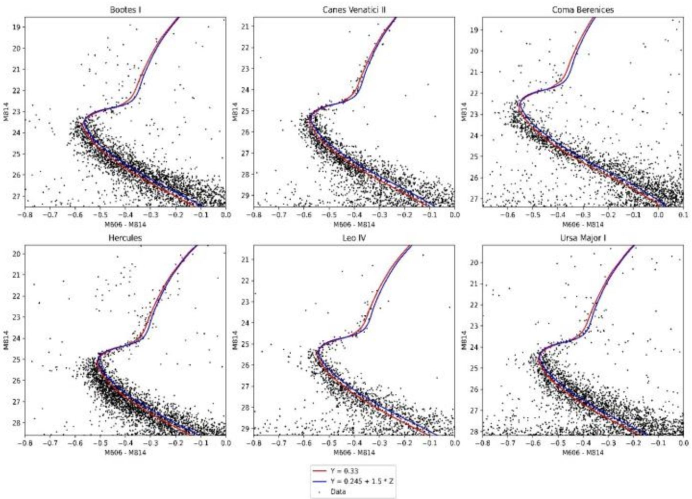

Figure 2: The colour-magnitude diagrams (F606W vs F606W-F814W) of six UFD galaxies are shown in this figure. The isochrones were generated with the aid of the Dartmouth Stellar Evolution Database[7].

CONCLUSIONS/ RECOMMENDATIONS

Finally, in conclusion, it is clear that the metallicities of the UFD galaxies were found to have extremely low metallicities. These extremely metal-poor stars were considered to have been the "first-born" stars created in the Universe. The CMD of the six UFDs look very similar, meaning that the population ages and metallicities are also very similar. These dim satellites (UFDs) are older than 10 Gyr with contrast to brighter dSphs. Moreover, the metallicity distributions, $[\alpha/Fe]$ and ages for the UFD galaxies were determined. They all show extremely low metallicity distributions $[Fe/H]$, which are nearly as low as that of the Milky Way stellar halo.

Finally, it was demonstrated that the UFDs are composed of old stellar populations.

According to calculations based on the cold dark matter concept, the local group contains more UFDs than previously detected. The missing satellite problem refers to the disparity between projected and observed numbers of UFDs (MSP).

The simulations based on the cold dark matter model reveal that the local group contains more UFDs than those observed so far. The discrepancy between the predicted and observed numbers of the UFDs is known as the missing satellite problem (MSP). Also, the spatial distributions of the BS candidates in the UFDs reveal that they are not young MS stars but mass-transfer BS stars. These results indicate that the gases in the UFD progenitors were removed more effectively than those of brighter dSphs when the initial star formation occurred. Furthermore, analysing some key properties such as the Main Sequence (MS), Horizontal Branch (HB), Sub Giant Branch (SGB) and Red Giant Branch (RGB) will be proposed in a later project.

[7] (http://stellar.dartmouth.edu/models/)

REFERENCES

Brown, T. M., Tumlinson, J., Geha, M., Simon, J. D., Vargas, L. C., Vandenberg, D. A., … Renzini, A. (2014). The quenching of the ultra-faint dwarf galaxies in the reionization era. *Astrophysical Journal*, 796(2), 1–13. Retrieved from https://doi.org/10.1088/0004-637X/796/2/91

Conroy, C. (2013). Modeling the panchromatic spectral energy distributions of galaxies. *Annual Review of Astronomy and Astrophysics*, 51(Faber 1972), 393–455. Retrieved from https://doi.org/10.1146/annurev-astro-082812-141017

D’Antona, F., Bellazzini, M., Caloi, V., Pecci, F. F., Galleti, S., & Rood, R. T. (2005). A Helium Spread among the Main-Sequence Stars in NGC 2808. *The Astrophysical Journal*, 631(2), 868–878. Retrieved from https://doi.org/10.1086/431968

Dotter, A., Chaboyer, B., Jevremović, D., Baron, E., Ferguson, J. W., Sarajedini, A., & Anderson, J. (2007). The ACS Survey of Galactic Globular Clusters. II. Stellar Evolution Tracks, Isochrones, Luminosity Functions, and Synthetic Horizontal-Branch Models. *The Astronomical Journal*, 134(1), 376–390. Retrieved from https://doi.org/10.1086/517915

Dotter, A., Chaboyer, B., Jevremović, D., Kostov, V., Baron, E., & Ferguson, J. W. (2008). The Dartmouth Stellar Evolution Database. *The Astrophysical Journal Supplement Series*, 178(1), 89–101. Retrieved from https://doi.org/10.1086/589654

Ferraro, F. R., Lanzoni, B., Dalessandro, E., Mucciarelli, A., & Lovisi, L. (2015). Blue Straggler Stars in Globular Clusters: A Powerful Tool to Probe the Internal Dynamical Evolution of Stellar Systems, 99–127. Retrieved from https://doi.org/10.1007/978-3-662-44434-4_5

Gnedin, O. Y., & Prieto, J. L. (2009). Formation of globular clusters in hierarchical cosmology: ART and science. *ESO Astrophysics Symposia*, 2009(2001), 323–330. Retrieved from https://doi.org/10.1007/978-3-540-76961-3_77

Jain, R., Vig, S., & Ghosh, S. K. (2019). Investigation of the globular cluster NGC 2808 with the ultra-violet imaging telescope. *Monthly Notices of the Royal Astronomical Society*, 485(2), 2877–2888. Retrieved from https://doi.org/10.1093/mnras/stz544

Journal, T. A. (2008). The Astrophysical Journal , 685: L9–L12, 2008 September 20
9–12.

Nardiello, D., Libralato, M., Piotto, G., Anderson, J., Bellini, A., Aparicio, A., … van der Marel, R. P. (2018). The Hubble Space Telescope UV Legacy Survey of Galactic Globular Clusters - XVII. Public Catalogue Release. *Monthly Notices of the Royal Astronomical Society*, 481(3), 3382–3393. Retrieved from https://doi.org/10.1093/mnras/sty2515

Okamoto, S., Arimoto, N., Yamada, Y., & Onodera, M. (2012). Stellar populations and structural properties of ultra faint dwarf galaxies, Canes Venatici I, Boötes I, Canes Venatici II, and Leo IV. *Astrophysical Journal*, 744(2). Retrieved from https://doi.org/10.1088/0004-637X/744/2/96

Willman, B., Blanton, M. R., West, A. A., Dalcanton, J. J., Hogg, D. W., Schneider, D. P., … Brinkmann, J. (2005). A New Milky Way Companion: Unusual Globular Cluster or Extreme Dwarf Satellite? *The Astronomical Journal*, 129(6), 2692–2700. Retrieved from https://doi.org/10.1086/430214

Wyse, R. F. G., & Gilmore, G. (2007). Observed properties of dark matter on small spatial scales. *Proceedings of the International Astronomical Union*, 3(S244), 44–52. Retrieved from https://doi.org/10.1017/S1743921307013828